The Benefits of Multimode Polarization Measurements and Frequency Selective Bolometers

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INTRODUCTION

The cosmic microwave background radiation (CMB) contains information about the details of the universe just prior to the decoupling of radiation and baryons at $z \sim 1100$, as well as the universe the CMB photons have since traversed. Degree-scale measurements of the temperature and polarization anisotropies of the CMB have and will continue to give us information about the universe at decoupling; few-arcminute angular scale measurements should tell us much about the structure with which the photons have interacted along their paths. For a detailed discussion of these effects and the information that can be gleaned from them, see Hu and Dodelson (2001) for a recent review.

We focus here on two science goals and the scope of instrumentation needed to target them. We also present a new idea for polarization and frequency multiplexed bolometric detectors that would enable extremely sensitive measurements of CMB polarization.

SCIENCE GOALS

Primordial B-mode polarization

The CMB is expected to be polarized at the level of a few percent of its temperature anisotropy. The largest polarization signal is the result of Compton scattering and plasma velocities induced by the density perturbations; it has been shown (Kamionkowski et al., 1997; Seljak, 1997; Zaldarriaga and Seljak, 1997) that this density-driven polarization signal has a pattern on the sky with zero curl, and is hence often called the "Grad" or "E-mode" polarization.

Gravity waves, presumably created at inflation and still present at $z \sim 1100$, will induce a polarization signal that is not curl-free, a component of which is thus known as the "curl" or "B-mode" polarization. The amplitude of this signal depends on the strength of gravity waves; inflation generally predicts a gravity wave signal whose amplitude is a function of the energy scale of inflation.

Figure 1 shows the predicted angular power spectrum of several CMB polarization signals. The E-mode polarization, created by density perturbations, is the largest pure polarization signal and will undoubtedly be the first detected. The true amplitude of the B-mode signals is very uncertain; here we have plotted it for a tensor to scalar ratio of T/S = 0.01. The ratio T/S, which is defined as ratio of the quadrupole temperature anisotropy (expressed in units of $\mu\mathrm{K}^2$) generated by tensors to that generated by scalars. T/S generally scales as $E^4_{\mathrm{inflation}}$ power, so a reduction by a factor of ten in the energy scale of inflation leads to a 10^4 times smaller B-mode power spectrum (in units of $\mu\mathrm{K}^2$) polarization signal, or a factor of 100 smaller in the temperature units of Figure 1.

Also shown in Figure 1 is a prediction of the B-mode polarization component that is inevitably caused by large scale structure lensing of the primordial E-mode polarization. This "foreground" peaks at higher ℓ than the primordial signal, but has a tail extending to low ℓ that could overwhelm the primordial signal. Knox and Song (2002) have pointed out that this lensing foreground cannot be perfectly subtracted; indeed, even with ideal subtraction one is limited to roughly 10% residuals. This motivates our use of the expected level of the lensing B-mode signal as a good first benchmark when considering potential sensitivities and foregrounds for a B-mode mapping experiment.

Dark Matter Mapping

CMB photons are lensed by large scale structure as they travel from the surface of last scattering at $z \sim 1100$ to our telescopes. Hu and Okamoto (2001) show that this lensing causes higher-order correlations in the CMB temperature and polarization anisotropies, which can in turn be used to reconstruct the gravitational potential along the line of sight. In this manner, maps of the CMB with few arcminute angular resolution can be used to "image" the dark matter along the line of sight between us and the surface of last scattering.

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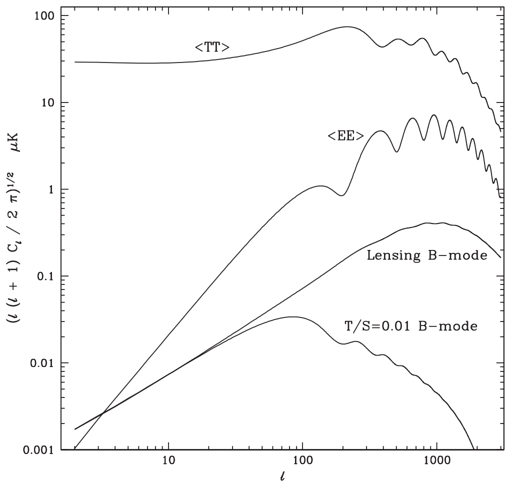

Figure 1: *CMB angular power spectra for a flat Λ-CDM model, with a tensor to scalar ratio of T/S = 0.01, calculated with CMBFAST (Seljak and Zaldarriaga, 1996). Gravitational lensing by large scale structure creates a B-mode foreground signal that will limit the depth to which primordial B-modes can be probed.*

Temperature anisotropies alone can make significant contributions to this process, but very high sensitivity polarization measurements improve the mass maps significantly on small scales. The sensitivity requirements are quite daunting: the "ultimate measurement" quoted by Hu and Okamoto (2001) calls for a sensitivity of 1μK-arcmin over a $10^\circ \times 10^\circ$ map with $4'$ angular resolution.

FOREGROUNDS

Galactic and extragalactic foregrounds have so far not been significant contaminants for CMB temperature anisotropy measurements made well away from the Galactic plane. This luck may hold for upcoming measurements of the E-mode polarization, but it is unlikely to continue deep into the era of B-mode searching. The evidence for this is given in Figure 2, where primordial E-mode and lensing B-mode signals are plotted on top of foreground models from Tegmark et al. (2000). If the primordial B-modes are at a level near or below the lensing B-mode foreground, it is very likely that foreground subtraction will be required to detect them.

INSTRUMENT REQUIREMENTS

Achieving the science goals described above poses several challenges. First, one must achieve the exquisite sensitivity needed to detect these effects. Second, monitoring and removing foregrounds requires multi-frequency coverage. Finally, systematic effects must be controlled at a very low level. We concentrate here on the first two requirements, but note in passing that observing both polarizations simultaneously in one resolution element, with detectors located very close to one another, has significant advantages for reducing systematic effects.

Current bolometric detectors are capable of achieving performance very near the background limit set by the statistics of the arrival of incident photons. The key to future, more sensitive instruments is not in improving individual detectors. Instead, it lies in catching more photons.

The ideal receiver will:

- cover the entire focal plane of the telescope, limited by aberrations,
- detect both linear polarizations at each position on the focal plane,
- use all the valuable bandwidth, eg from 30 to 300 GHz everywhere on the focal plane,
- separate this bandwidth into many bands to enable foreground subtraction,
- achieve photon noise limited performance in all bands,

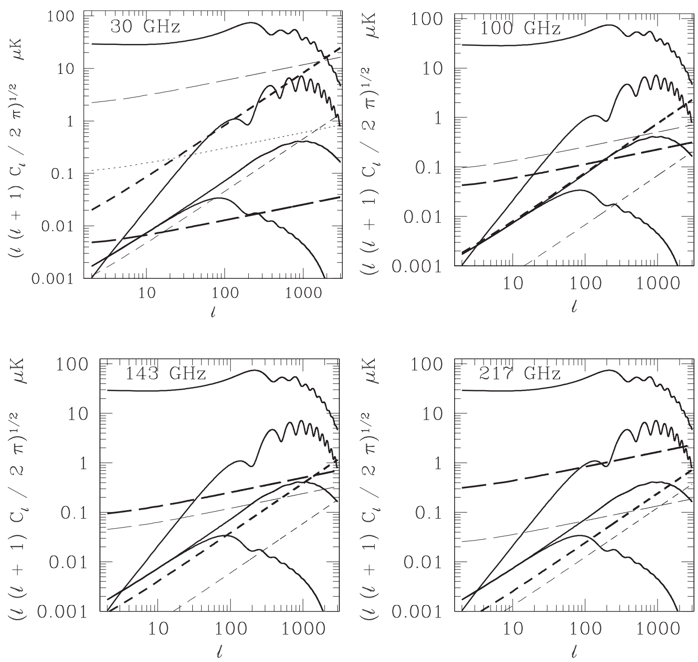

Figure 2: *In bold solid lines are the same CMB angular power spectra as Figure 1. The other lines show B-mode foregrounds calculated from the "MID" model of Tegmark et al. (2000). The line key is: synchrotron, regular long-dash; vibrational dust, bold long-dash; infrared point sources, regular short-dash; radio point sources, bold short-dash; rotational dust, regular short-long dash. These predictions are for sky greater than* 30° *from the galactic plane; factors of several will be gained by concentrating on smaller regions of low galactic emission. While these polarization foreground models remain fairly uncertain, it is very likely that multiple frequency bands will be needed in any B-mode measurement.*

Thus, the target is to build a wide-bandwidth detector system that tiles the focal plane with pixels that are each polarization and color sensitive. For telescope systems with large throughput ($A\Omega$), single mode systems (eg antenna coupled arrays, single-mode horns, or bare arrays with pixels smaller than the diffraction spot) will require a very large number of detectors to achieve this goal. For example, the proposed 8m South Pole Telescope will have a roughly 1° field of view and $1.3'$ diffraction limited beams at 150 GHz given a conservative edge taper on the primary. To perfectly fill this field of view requires nearly 1700 detectors at each color and polarization. A five-color, 2 polarization system would require nearly 17,000 detectors in the receiver. For observations which require the high total system $A\Omega$ but not the high single-mode angular resolution, this is unnecessary complication without increased sensitivity.

In fact, obtaining both polarization and frequency sensitivity is a tough challenge for single-mode, single-wafer systems. Antenna-coupled systems are being proposed with either polarization or frequency sensitivity, but the combination is more difficult to engineer.

We discuss here a multimode technique that could achieve the optimum polarization and color sensitivity for such a focal plane, while using significantly fewer detectors. This multimode technique trades off angular resolution for the number of detectors, and enables a simple method of polarization and frequency multiplexing in the focal plane.

A MULTIMODE APPROACH

In the photon noise limit, a single detector sensitive to m modes is exactly as sensitive as m detectors each sensitive to a single mode. The presence of detector noise favors the multimode system. Thus, if angular resolution is not an issue, a focal plane tiled with N single-mode detectors can instead be tiled with N/m multimode detectors, with no loss of sensitivity.

The Frequency Selective Bolometer (FSB) system (Kowitt et al., 1996) provides a multimode scheme for tiling a focal plane with color multiplexed pixels. The photons that enter each pixel are channeled along a light pipe, where they encounter a series of resonant bolometers and backshorts. These resonant bolometers absorb the photons in many close-packed bands over a very broad range of frequencies. A four band FSB system has been prototyped and tested as a proving ground for this concept. Here we describe a scheme for adding polarization sensitivity to the FSB's, and the scientific promise if this goal were realized.

The FSB relies on a resonant bolometer, constructed of a planar sheet array of resistive crosses mounted across the light pipe. A similar but more conductive sheet of crosses placed $\lambda/4$ behind the bolometer acts as a resonant quarter-wave backshort. These elements are similar to the capacitive, inductive, and resonant mesh filter systems used in many receivers and described by many authors (Ulrich, 1967, 1968; Cunningham, 1983). In the FSB, the bolometer absorbs photons in a band around its resonant frequency; other wavelength photons pass through the bolometer-backshort combination and proceed down the lightpipe. A single lightpipe contains several bolometer-backshort pairs tuned to different resonant frequencies, thus absorbing (and detecting) light in several bands.

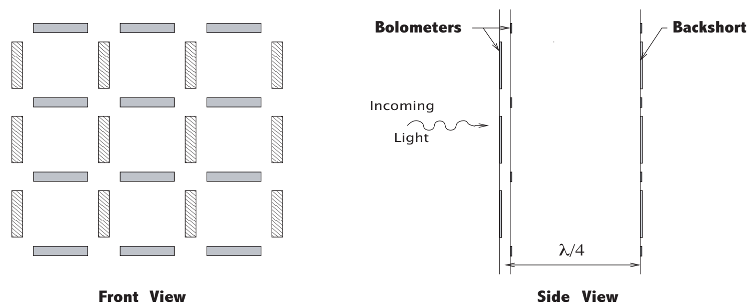

Figure 3: *This sketch of the PFSB shows the resonant structure face-on on the left with the vertical resistive bars and horizontal resistive bars placed on separate membranes separating the measurement of the power in the two polarizations. On the right is shown how these resistive bars are placed λ/4 in front of a resonant short. The total structure has a controllable frequency dependence for the transmission, reflection and absorption permitting these elements to be stacked to make a multi-frequency pixel.*

The PFSB is an extension of the FSB; here, the resistive crosses on the bolometer are separated into their horizontal bar and vertical bar constituents and offset from one another as shown in Figure 3. The horizontal and vertical bars are then placed on separate sheets offset along the lightpipe, forming two separate bolometers. Each of these bolometers is sensitive to a single polarization; as long as they are separated by a distance along the guide of $d \ll \lambda/4$, they can use a common backshort.

While the concept is simple, there are two difficult issues that need further modelling and testing. First, polarization must be preserved as the wave travels down the lightpipe through several sets of detector-backshort pairs. In an ideal circular guide, this would not be an issue; it is an issue given the breaks in the light guide necessary for mounting the previous bolometers. Second, it is highly desirable to have similar and symmetric beam patterns in each polarization, to minimize coupling of the polarization difference to temperature anisotropies on the sky. For this reason, the PFSB is probably most ideal when operating in the many-mode regime.

SENSITIVITY CALCULATIONS

Obtaining the sensitivity required to reach these science goals is a significant challenge, and will require very efficient use of the focal plane area by polarization and frequency multiplexing. To illustrate this challenge, we have calculated the sensitivity to CMB polarization for two model bolometric instruments designed to measure B-mode polarization CMB signals, both idealized as limited only by photon noise and bolometer G noise. One of the models is for a space-based instrument with a 2.5 m telescope cooled to 50K. The second is a ground-based 8 m telescope at South Pole. The photon noise is calculated for the CMB itself, the hot optics, and in the case of the ground-based instrument the emission from the atmosphere.

In both cases we model the bolometric detectors to have no appreciable Johnson noise, as is possible with TES thermistors. We assume that the thermal conductance of the detector is tailored to the radiation load, and the devices are voltage biased with the electrical power equal to the radiation load. We assume that the detector element runs 100 mK hotter than the bath temperature (300mK). For the South Pole Telescope, the photon noise dominates over bolometer noise in all frequency bands. For the Space mission the photon noise dominates bolometer noise in all bands except at 90 GHz, where they are comparable. The results of this modelling is shown in Table 6.1.

Are these sensitivities sufficient to achieve the science goals? Hu and Okamoto (2001) develop the sky sensitivity requirements for mapping the dark matter using weak lensing of the CMB. Knox and Song (2002) have calculated

Table 6.1: Assumptions for Sensitivity Calculations

Condition	South Pole (lensing B-modes)	Space-based (primordial B-modes)
Reference sky sensitivity	1μK-arcmin	1μK-arcmin
Map size	100 sq. degree	400 sq. deg
Total Required Weight	3.6×10^{17}K^{-2}	1.4×10^{18}K^{-2}
Telescope		
Primary Diameter	$D = 8$m	$D = 2.5$m
Edge Taper	20 dB	20 dB
Usable field diameter	1°	2°
Pixels		
Pixel Diameter	$4'$ FWHM	$12'$ FWHM
Number of modes/pix@150GHz	4.5	4
Optical efficiency	0.5	0.5
Number of pixels	~ 300	$\sim$130
Photon background noise		
Hot optics	$\epsilon = 0.01$ $T = 250$K	$\epsilon = 0.005$ $T = 50$K
Atmosphere	$\epsilon = 0.04$ $T = 250$K	none
CMB	$\epsilon = 1.0$ $T = 2.7$K	$\epsilon = 1.0$ $T = 2.7$K
Calculated Background limit	BLIP$= 5 \times 10^{-17}$W Hz$^{-0.5}$	BLIP$= 1 \times 10^{-17}$W Hz$^{-0.5}$
Bolometer noise, G-noise only, $T_{\rm bath} = 0.3$K, $T_{\rm det} = 0.4$K, $P_{\rm elect} = P_{\rm rad}$, @150GHz	NEP$\sim 4 \times 10^{-17}$W Hz$^{-0.5}$	NEP$\sim 1 \times 10^{-17}$W Hz$^{-0.5}$

Table 6.2: Model PFSB Instrument Sensitivity

Frequency GHz	Bandwidth (GHz)	South Pole Telescope (lensing B-modes) $\tau_{\rm int}$ (days)	NET (all pix) (μK sec$^{0.5}$)	Space-based Telescope (primordial B-modes) $\tau_{\rm int}$ (days)	NET (all pix) (μK sec$^{0.5}$)
90	30	800	14	710	6.5
150	30	660	13	350	4.6
220	30	1100	16	340	4.5
270	40	1600	19	380	4.7
315	50	2640	25	530	5.6
470	50	-	130	-	25
Using all (no foreground removal)		210	7.2	85	2.2

the limits to the primordial B-mode detection as a function sensitivity. Both papers compare to a reference instrument with a sky sensitivity of 1μK-arcmin. We use the two model instruments to estimate the integration time required to reach this level; results are presented in Table 6.2.

Obtaining these "reference instrument" sensitivities for an appreciable sky fraction is clearly an enormous challenge. Approaching these goals will clearly require a high degree of multiplexing: the system must cover as large a solid angle as possible simultaneously, the system should measure all the required frequency bands simultaneously, and the system should measure both polarization states in each pixel at the same time.

Using a PFSB system with five spectral channels on the South Pole Telescope, filling a 1 degree field with $4'$pixels, permits the system to measure a 10°x 10°region of the sky to the reference sensitivity in less than 200 days of integration. The limiting factor is the photon noise from the atmosphere emission; we have assumed there is no additional atmospheric noise from fluctuations in its emission because these fluctuations are expected to be relatively coherent across the array and relatively unpolarized. Thus, polarization differencing and array-average subtraction should greatly reduce their effects. The number of detectors required to completely fill and multiplex this focal plane is 3000: 300 pixels, 5 frequencies, and 2 polarizations. The required individual detector sensitivities is well within that of current standard bolometers running at 300 mK bath temperature.

For the space-based mission, the photon noise (from the 50K optics and the CMB) and the detector noise are comparable if the instrument is run with 300mK detectors. A factor of two gain would be realized with a colder bath temperature. The smaller space based telescope used in this multimode fashion still has more than sufficient angular resolution to measure the primordial B-modes.

Another representation of the potential statistical power of the PFSB technology on these telescope platforms is shown in Figure 4. Here, we plot the errors on B-mode power spectra given a year of integration with each platform, using only the 150GHz channel. Clearly the statistical power is there to do very interesting science; the unknown challenges are controlling systematic effects and removing foregrounds.

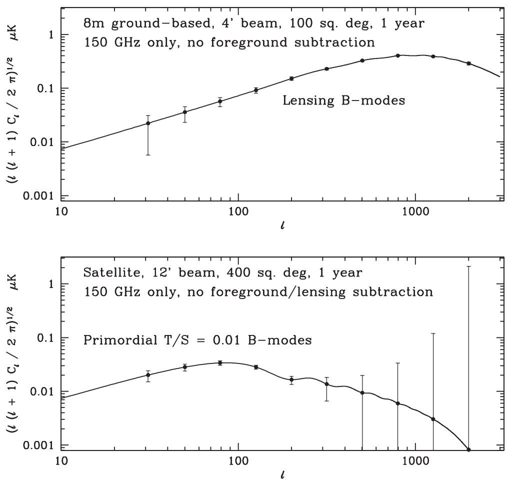

Figure 4: *The top panel shows the statistical power a PFSB system on the South Pole telescope could bring to bear at small angular scales, measuring the lensing-induced B-mode signal. The bottom panel shows a similar calculation for the space mission, with the primordial B-modes as a target. In both cases, one year of the 150GHz channel has been used, and the effects of foreground subtraction are not considered.*

CONCLUSION

We have described a new concept for multimode polarization and frequency selective bolometers which could be used to maximize receiver sensitivity and foreground rejection. This concept has the advantage of allowing many closely packed bands over a very wide bandwidth. It can achieve these sensitivity goals while using a significantly reduced number of detectors relative to single-mode techniques. Calculation of sensitivities with realistic telescope systems shows that very ambitious CMB B-mode science may eventually be within reach.

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